Water for a Healthy Country

An Ecosystem Assessment Framework to Guide Management of the Coorong

Final Report of the CLLAMMecology Research Cluster

July 2009
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The Water for a Healthy Country National Research Flagship is a research partnership between CSIRO, state and Australian governments, private and public industry and other research providers. The Flagship aims to achieve a tenfold increase in the economic, social and environmental benefits from water by 2025.

The Australian Government, through the Collaboration Fund, provides $97M over seven years to the National Research Flagships to further enhance collaboration between CSIRO, Australian universities and other publicly funded research agencies, enabling the skills of the wider research community to be applied to the major national challenges targeted by the Flagships initiative.

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Foreword

The Coorong, Lower Lakes and Murray Mouth (CLLAMM) region of the River Murray is an environmental asset of international significance. Lack of inflows from the Murray-Darling Basin and rising salinity have degraded the wetlands and significantly changed the ecological character of the region. Until recently, ecological response to these changes and to management interventions was largely unknown.

To address this CSIRO’s Water for a Healthy Country National Research Flagship established the Coorong Lower Lakes and Murray Mouth ecology Cluster (CLLAMMecology) in late 2006. It was the region’s first comprehensive research program, and one of the first Clusters supported by the National Research Flagship Collaboration Fund, a $97 million federal government initiative to support collaboration within the national innovation system.

The three-year $5.3 million initiative was tasked with developing better information and tools to support management initiatives to halt and reverse the degradation of the Coorong and Murray Mouth. It brought together researchers from key institutions, including the University of Adelaide, Flinders University, and the South Australian Research and Development Institute (SARDI) Aquatic Sciences.

In what was to become the largest research project examining the response of estuarine species to environmental flows in the region, CLLAMMecology brought together hydrodynamics, spatial analysis and bird and fish ecology specialists to provide a whole-of-system approach to water management tools for ecological outcomes.

This report summarises the key outcomes of the Cluster, which centre on the delivery of ecological knowledge of the region and the development of a comprehensive framework to evaluate the potential outcomes of management interventions on the ecological character of the Coorong and Murray Mouth region. The framework allows managers to evaluate how to best use the available management levers, such as environmental flows and dredging the Murray Mouth, to maximise environmental outcomes.

This report is part of a series summarising the outputs of the CLLAMMecology Research Cluster. Previous reports and additional information is found at: http://www.csiro.au/partnerships/CLLAMMecologyCluster.html

Tom Hatton
Flagship Director
Acknowledgements

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We also acknowledge the contribution of several other funding agencies, including Land & Water Australia, the Fisheries Research and Development Corporation, SA Water, the Murray Darling Basin Commission’s (now the Murray-Darling Basin Authority) The Living Murray program and the SA Murray-Darling Basin Natural Resources Management Board.

Other research partners included Geoscience Australia, the WA Centre for Water Research, and the Flinders Research Centre for Coastal and Catchment Environments. We also thank Joseph Davis and the Murray-Darling Basin Authority for providing River Murray flow information for the scenario analyses.

The objectives of this program have been endorsed by the SA Department for Environment and Heritage, SA Department of Water, Land and Biodiversity Conservation, SA Murray-Darling Basin NRM Board and Murray-Darling Basin Commission.

The CLLAMMecology Research Cluster was managed by a committee chaired by Anthony Cheshire and consisting of Brenton Grear, Richard Brown, Glynn Ricketts, Ian Prosser, Sébastien Lamontagne, David Paton, Jason Tanner, Peter Fairweather, Mike Geddes and Justin Brookes.

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## Glossary

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<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMR</td>
<td>Nuclear Magnetic Resonance spectroscopy.</td>
</tr>
<tr>
<td>Advection</td>
<td>The transfer of salt or other dissolved substances by horizontal water motions.</td>
</tr>
<tr>
<td>AHD</td>
<td>Australian Height Datum. The measure of elevation above sea level.</td>
</tr>
<tr>
<td>Bathymetry</td>
<td>A map showing water depth.</td>
</tr>
<tr>
<td>Benthic</td>
<td>Species that thrive on the bottom of a water body, i.e., benthic algae can thrive on the bottom of lakes.</td>
</tr>
<tr>
<td>Cyanobacteria</td>
<td>Aquatic bacteria that can photosynthesise.</td>
</tr>
<tr>
<td>Diatoms</td>
<td>Any of numerous microscopic, unicellular, marine or freshwater algae having siliceous cell walls.</td>
</tr>
<tr>
<td>δ (&quot;del&quot;)</td>
<td>A standardised measurement of the ratio of one stable isotope to another for a particular element. For example, δ(^{13})C represents the abundance of (^{13})C relative to the more common (^{12})C isotope in a carbon containing substance.</td>
</tr>
<tr>
<td>Hydrodynamics</td>
<td>The study of water movement and its causes.</td>
</tr>
<tr>
<td>Hypersaline</td>
<td>Water that is much saltier than seawater.</td>
</tr>
<tr>
<td>kmol</td>
<td>A unit for the number of atoms or molecules. 1 kmol = (6 \cdot 10^{26}) atoms or molecules.</td>
</tr>
<tr>
<td>Lacustrine</td>
<td>Of, or relating to a lake.</td>
</tr>
<tr>
<td>Limnological</td>
<td>The study of freshwater bodies such as lakes, including their physical, geographical and biological features.</td>
</tr>
<tr>
<td>Macrophytes</td>
<td>Literally large water plants referring to plants that are not algae. They may be either floating or rooted.</td>
</tr>
<tr>
<td>Osmoregulation</td>
<td>The active regulation by organisms of the salt content within their internal fluids.</td>
</tr>
<tr>
<td>Pelagic</td>
<td>Pertaining to the water column as opposed to benthic.</td>
</tr>
</tbody>
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Executive Summary

Background
Located south-east of Adelaide in South Australia, the Coorong, Lower Lakes and Murray Mouth (CLLAMM) comprise one of Australia’s largest wetland systems. The region is of great habitat significance for migratory waterbirds. It is listed as a Wetland of International Significance under the Ramsar Convention and recognised as an ‘icon site’ under the Murray-Darling Basin Authority program, The Living Murray. The region also supports a varied economy based on agriculture, fisheries and tourism, and it is the traditional country of the Ngarrindjeri Nation.

Lakes Alexandrina and Albert are two connected large freshwater lakes which comprise the Lower Lakes. The River Murray flows into Lake Alexandrina, which in turn is separated from the Coorong by a series of barrages constructed in the late 1930s. Flows from Lake Alexandrina to the Coorong can be controlled by opening gates in the barrages. The Coorong is connected to the sea via a narrow channel that is subject to infilling and scouring on a seasonal basis depending on whether the water is flowing through the barrages or not. The Murray Mouth section of the Coorong extends from this connecting channel north-westwards to Goolwa Barrage and south-eastwards to the south end of Tauwitcherie Barrage, where the Coorong widens into the North Lagoon. A narrow and shallow channel in the vicinity of Parnka Point separates the North Lagoon from the South Lagoon, which is the third major component of the system. A network of drains (the Upper South East Drainage Scheme) also discharges small volumes of water to the southern end of the South Lagoon.

Coorong water levels vary at daily to seasonal time scales creating habitats including periodically inundated mudflats, which are ideal for shorebirds. Typically, the Coorong has a strong salinity gradient along its 110 km length. When the barrages are flowing, water can be near fresh at its Mouth end and when they are not seawater salinity prevails in this region. Towards the southeastern end of the Coorong, salinity increases steadily due to evaporation. Frequently, salinity in the South Lagoon is substantially above that of seawater (hypersaline condition). The salinity variation representing estuarine, marine and hypersaline conditions supports different ecological communities.

Modifications to the flow regime of the River Murray have resulted in a significant change to the ecological character of the region since its listing as a Ramsar wetland in 1985. Currently, consumptive use of water across the Murray-Darling Basin has reduced the average annual stream flow at the Murray Mouth by 61% (from 12,333 GL/year to 4733 GL/year). In combination with a regional drought in the Basin, inflows to the Coorong have been especially low since 2002, with no inflow recorded since 2006. This has resulted in the siltation of the Murray Mouth channel and the extreme hypersalinisation of the South Lagoon, where salinity is currently in excess of four times seawater. These changes to the water regime of the River Murray have been linked to a decline in abundance of a number of fish and waterbird species in the Coorong.

While a number of management initiatives are underway to address the environmental decline of the region, few tools have been available to help design and optimise long-term management intervention strategies.

Project aim and scope
CLLAMMeconomy is a collaborative research program that aimed to improve ecological knowledge about the CLLAMM region and to develop an ecological framework to support the design of longer-term management interventions. The focus of the CLLAMMeconomy initiative has been the Coorong, but some ecological research has also been undertaken in the Lower Lakes with the goal of understanding their role in mediating nutrient inputs to the Coorong through barrage outflows.
The basis of the framework was to use a ‘systems’ approach to the Coorong and Murray Mouth region, which involved identifying the available management levers, how they interact to influence key ecosystem drivers, and finally to understand how ecological communities respond to changes in ecosystem drivers. The potential management levers for the Coorong are environmental flows from the barrages, water releases from the Upper South-East Drainage scheme, and dredging of the Murray Mouth channel connecting to the sea. Other engineering interventions, such as pumping hypersaline water from the South Lagoon to the sea, are also being considered as potential management levers.

The study strategy is based on the presumption that the two key ecosystem drivers in the Coorong are the water level and salinity regimes.

**CLLAMMecology Research Program**

The CLLAMMecology research program comprises three linked components that constitute the building blocks for the ecosystem framework. These are:

- The development of a hydrodynamic model of the Coorong suitable for use in longer-term (30–100 years) forecasting and hindcasting of changes in the water level and salinity regimes.
- A field program to study the ecology of key species of invertebrates, fish and waterbirds and to quantify key ecological processes, such as nutrient cycling and food webs.
- The development of ecological models to predict the distribution of key species, habitats, and of alternative ecosystem states as they would respond to water level, salinity, and other environmental drivers.

Twenty potential longer-term climate change and management scenarios for the Coorong were investigated to illustrate how the framework can be used. For the climate component, scenarios included different River Murray flow forecasts under a 2030 climate in combination with different estimates for sea level rise. The evaluation of the potential effectiveness of different management levers was made by including scenarios of increased environmental flows over the barrages, of different levels of water releases from the Upper South East Drainage Scheme to the South Lagoon, and Murray Mouth channel dredging.

The research occurred during a period (2006–08) when there was virtually no freshwater inflow through the barrages to the Coorong. This provided a unique opportunity to learn about the ecology of this system under extreme environmental conditions. Historical water quality and ecological information from periods when River Murray flows occurred was also used.

**Key findings and outputs**

*Hydrodynamics and salinity*

- River Murray flows play many roles in determining the physical condition of the Coorong, including by scouring the Mouth channel and thereby maintaining connectivity with the sea, by introducing freshwater into the North Lagoon which eventually makes its way along the system, and by causing water to back up into the Coorong and so enhance exchange between the two lagoons.
- An extreme salinity gradient developed in the Coorong during the study, in the absence of freshwater inflow. Marine to slightly hypersaline conditions (up to 2x seawater) were maintained in the Murray Mouth area by exchange with the Southern Ocean. However, as a result of evaporation and more limited exchange, moderately hypersaline conditions (2-4x seawater) occurred in the North Lagoon and extremely hypersaline conditions (more than 4x seawater) occurred in the South Lagoon.
- A hydrodynamic model of the Coorong and Murray Mouth suitable for longer-term scenario analyses was developed.
Nutrient inputs and cycling

- The Lower Lakes were found to be a net sink for phosphorus, nitrate and silicon flowing in from the River Murray, but they are an overall source of organic nitrogen. Nevertheless, the flows through the barrages from Lake Alexandrina are an important source of nutrients and organic matter to the Coorong and benefit its food webs.

- Nutrient inputs from the Lower Lakes during high flow years are stored in the Coorong and can be recycled from the sediment pool during low flow years. This process will help maintain ecological productivity in the Coorong during low flow years.

- Studies on nutrient cycling and primary production highlighted some of the unusual biogeochemical features of the Coorong. Nutrient and chlorophyll a concentrations (an indicator of algal biomass) increased with increasing salinity. However, more algal production occurred on the sediment surface than in the water column, consistent with the shallow average depth of the Coorong allowing light to reach the bottom. Regional groundwater discharge may be an additional source of nutrients to the South Lagoon.

Ecology of key species

- The aquatic grass *Ruppia tuberosa* was absent from the South Lagoon in winter 2008 but had started to colonise parts of the North Lagoon. This aquatic plant was formerly abundant in the South Lagoon and was a key food source for waterbirds. The capacity for *Ruppia* to recolonise the South Lagoon if favourable conditions return is currently severely compromised by the low abundance of live propagules (turions and seeds) stored in sediments.

- Salinity was a key limiting factor in the distribution of fish and invertebrates in the Coorong. The highest diversity of fish and invertebrates was in the Murray Mouth area, where salinity remained less than twice seawater. Smallmouth Hardyhead *Atherinosoma microstoma*, a fish species formerly abundant in the South Lagoon, was either absent or only found at low densities in that area in 2006–07. However, the Australian Brine Shrimp *Parartemia zietziana* has recently colonised the South Lagoon.

- Declines in the abundance of key waterbird species observed between 1985 and 2000 have intensified in recent years. Decline was most pronounced in the South Lagoon and was attributed to the disappearance of key food sources, such as *Ruppia* and Smallmouth Hardyhead. However, Banded Stilt *Cladorhyncus leucocephalus* abundance in the South Lagoon has increased in recent years, owing to the recent appearance of brine shrimp, an important food source for this species.

Habitat mapping

- Combining a number of data sources, the distribution of 24 wetland types was mapped across the region. This wetland distribution is representative of conditions between 2000 and 2005 and can be used as a baseline to evaluate changes in future wetland distribution.

- A Digital Elevation Model (DEM) of the Coorong was assembled which, for the first time, enabled a seamless bathymetry of the region. When combined with the hydrodynamic model and with a sediment map, the DEM can be used to predict the distribution of key habitats in the region. For example, it is now possible to identify the location of mudflats with a particular sediment type and inundation regime. These models can be used to help understand the distribution of shorebirds.

- Models were also developed predicting the spatial distribution of four key fish species (*Yelloweye Mullet Aldrichetta fosteri*, Smallmouth Hardyhead, Greenback Flounder *Rhombosolea taprina* and Tamar River Goby *Afurcagobius tamarensis*) based on salinity tolerance.
Ecological modelling

- An ecosystem state-and-transition model was developed for the Coorong using data collected between 1999 to 2007. Eight potential ecosystem states were identified, of which four were typical of no flow over the barrages.

- The environmental variables that determined switches from one state to another at a particular location included whether tidal influence was present, the average water level and the average salinity. No flow over the barrages for more than a year was found to be a key threshold to initiate switches in ecosystem states across the Coorong.

Scenario analyses

- Climate and extraction from the River Murray will be the two strongest determinants of the ecological condition of the Coorong in the future. At current extraction levels across the Murray-Darling Basin, the forecast reductions in River Murray inflows to the region under a ‘dry’ future climate scenario would lead to significant further ecological degradation of the Coorong. However, sea level rise may partially ameliorate the condition of the Coorong under this ‘dry’ scenario. While increased Upper South East Drainage scheme releases and Murray Mouth dredging may bring some environmental benefits, the most effective management lever in the scenario analyses was clearly increased environmental flows from the barrages.

Project legacy

Foundation studies

This project has significantly advanced the ecological knowledge of the Coorong. The limnological surveys of the Lower Lakes undertaken during CLLAMMecology are also the most detailed to date for this system, in particular with regards to offshore water quality. The coordinated research effort allowed the study of multiple aspects of the ecology of the Coorong, including topics, such as nutrient cycling, which had received limited attention before. Because this study occurred during a period when there was no flow over the barrages, it provides an ecological ‘baseline’ to compare with future environmental flow experiments for the region.

Ecological Framework

Knowledge of the Coorong’s ecological system obtained through CLLAMMecology and previous studies has been encapsulated in a modelling framework that can be used to support effective management. The framework has two basic components:

- A hydrodynamic model to forecast changes in water level and salinity in the Coorong and Murray Mouth at decadal scales and longer in response to manipulations of barrage flows, flows from the Upper South East Drainage scheme, climate change and variability, and engineering interventions, and

- Ecological models to predict changes in the distribution of key species, habitats, and ecosystem states following changes in water level, salinity and other factors.

The framework’s ability to determine ecological impact from physical manipulation of the system is not only powerful, but also one of the few examples of its kind in Australia and worldwide.

The results of the study can be found in a series of reports available through the web. In addition, a metadatabase of the information collected during the study has been compiled and can also be accessed through the web.

The framework does not consider the potential social, economic or cultural impacts of management intervention in the Coorong, but could be used to support the analysis of such impacts.
Conclusion and recommendations

Through CLLAMMecology, a scientifically verified understanding of the linkages between physical interventions and ecological impacts has been developed which is encapsulated in a modelling framework. As this understanding and framework are sufficiently robust, it is recommended that the framework be used to guide management of the Coorong for achieving ecological objectives.

The principal focus of CLLAMMecology was on the Coorong because this was the region of concern for management at the time the study was designed. Since then, the ecological status of the Lower Lakes has also degraded following a period with very low River Murray inflows. The approach undertaken during CLLAMMecology to understand the relationships between management levers, key environmental drivers and their impact on ecological processes is also applicable to the Lower Lakes. CLLAMMecology therefore recommends a similar framework for management of the Lower Lakes.

While progress was made, there remain a number of knowledge gaps in the ecology of the Coorong. This is due, in part, to the most detailed studies of the region having been made during a period when it was gradually degrading (especially from the late 1990s onward). Many knowledge gaps could be addressed by studying the ecology of the Coorong during periods when significant freshwater flows occur through the barrages. CLLAMMecology recommends using future environmental flows from the barrages as opportunities to improve the understanding of the ecology of the Coorong. As significant flows through the barrages are unlikely to occur in the next few years, there is an opportunity to design and plan a follow-up study to CLLAMMecology targeting a period with significant environmental flows to the Coorong.
1. Introduction

CLLAMMecology is a collaborative research program that aimed to improve ecological knowledge about the Coorong, Lower Lakes and Murray Mouth (CLLAMM) region and to develop an ecological framework to help design longer-term management interventions. Facilitated by CSIRO’s Water for a Healthy Country Flagship, the CLLAMMecology research cluster was a partnership between CSIRO, the University of Adelaide, Flinders University, and South Australian Research and Development Institute (SARDI) Aquatic Sciences. The research cluster was supported by a number of management agencies including the South Australian Department for Environment and Heritage, the Department of Water, Land and Biodiversity Conservation, the SA Murray-Darling Basin Natural Resources Management Board, and the Murray-Darling Basin Authority. Additional research and funding partners included Land & Water Australia, Geoscience Australia, and the Fisheries Research and Development Corporation.

1.1. The Coorong, Lower Lakes and Murray Mouth region

Located south-east of Adelaide in South Australia, the CLLAMM comprise one of Australia’s largest wetland systems (Figure 1.1). The region is of great habitat significance for migratory waterbirds. It is listed as a Wetland of International Significance under the Ramsar Convention, the Japan-Australia Migratory Bird Agreement (JAMBA) and the China-Australia Migratory Bird Agreement (CAMBA). It is also a designated ‘icon site’ under the Murray-Darling Basin Authority program The Living Murray. (Murray-Darling Basin Commission 2006; Phillips and Muller 2006). The region also supports a varied economy based on agriculture, fisheries and tourism, and it is the traditional country of the Ngarrindjeri Nation (Ngarrindjeri Nation 2007).

Lakes Alexandrina and Albert are two connected large freshwater lakes which comprise the Lower Lakes. The River Murray flows into Lake Alexandrina, which in turn is separated from the Coorong by a series of barrages constructed in the late 1930s. Flows from Lake Alexandrina to the Coorong can be controlled by opening gates in the barrages. The Coorong is connected to the sea via a narrow channel that is subject to infilling and scouring on a seasonal basis depending on whether the water is flowing through the barrages or not. The Murray Mouth section of the Coorong extends from this connecting channel north-westwards to Goolwa Barrage and south-eastwards to the south end of Tauwitcherie Barrage, where the Coorong widens into the North Lagoon. A narrow and shallow channel in the vicinity of Parnka Point separates the North Lagoon from the South Lagoon, which is the third major component of the system. A network of drains (the Upper South East Drainage (USED) scheme) also discharges small volumes of water (~7 GL/year) to the southern end of the South Lagoon. This amount may increase in the future following proposed diversions from a system of drains further south.

Coorong water levels vary at daily to seasonal time scales creating habitats including periodically inundated mudflats, which are ideal for shorebirds. Typically, the Coorong has a strong salinity gradient along its 110 km length. When the barrages are flowing, water can be near fresh at its Mouth end and when they are not seawater salinity prevails in this region. Towards the southeastern end of the Coorong, salinity increases steadily due to evaporation. Frequently, salinity in the South Lagoon is substantially above that of seawater (hypersaline condition). The salinity variation representing estuarine, marine and hypersaline conditions supports different ecological communities.
Figure 1.1. Map of the Coorong and surrounding region, showing the location of the 12 focal sites of the CLLAMMecology research program.

1.2. Changed flow regimes impact on regional ecology

The magnitude and the timing of River Murray inflows to the region have changed significantly since European settlement due to water resources development in the Murray-Darling Basin. Consumptive water use across the Basin has reduced the average annual streamflow at the Murray Mouth by 61% (from 12,333 GL/year to 4733 GL/year; CSIRO 2008). In the absence of water resource development, the river would cease to flow at the mouth only 1% of the time, whereas under current water use, this increases to 40% of the time, on average. The average period between flood events large enough to flush the Murray Mouth has also increased from two to nearly six years (CSIRO 2008). In combination with a regional drought in the Basin, inflows to the Coorong from the Lower Lakes barrages have been especially low since 2002, with no inflow recorded since 2006. This has resulted in the siltation of the Murray Mouth channel and the hypersalinisation of the South Lagoon, where salinity is currently in excess of four times seawater.

Changes to the flow regime of the River Murray have resulted in significant changes to the ecological character of the region since its listing as a RAMSAR wetland in 1985 (Phillips and Muller 2006). Underlying changes in the ecological character of the Coorong probably started earlier, especially with the construction of the Lower Lakes barrages (Jensen et al. 2000). It is now recognised that the environmental assets of the region are degraded and require
management intervention to meet international and national obligations in the protection of migratory waterbirds and other species. Until recently, few tools were available to aid planning of longer-term management interventions for this geographically and biophysically complex environment. In particular, limited means were available to quantify the potential benefits of increased environmental flows to the region because these flows impact on the region’s ecosystems in several complex ways.

1.3. Developing a ‘system’ vision for the region

At the time the study was planned (2005), management agencies were primarily concerned with improving the conditions of the Coorong and Murray Mouth area of the CLLAMM region. Thus, the project framework was specifically developed for the area downstream of the Lower Lakes barrages only. Some ecological research also took place in the Lower Lakes, such as understanding their role in controlling nutrient inputs to the Coorong and Murray Mouth through barrage outflows.

The basis of the framework was to use a ‘system’ approach to the Coorong and Murray Mouth region, which involved identifying the available management levers, and how they interact to influence key ecosystem drivers (Figure 1.2; Lamontagne et al. 2004), and finally to understand how ecological communities respond to changes in ecosystem drivers. The potential management levers for the Coorong and Murray Mouth are environmental flows from the Lower Lakes barrages, water releases from the USED scheme, and dredging of the Murray Mouth channel. Engineering interventions, such as pumping Coorong hypersaline water to the sea, provide other potential management levers. The premise of this approach is that the key ecosystem drivers in the Coorong are the water level and salinity regimes.

**Figure 1.2.** Conceptual representation of a management planning framework for the Coorong using a ‘system’ approach. The aim is to identify the potential ‘levers’ for management intervention and to understand how they act upon biological communities through their influence on key ecosystem ‘drivers’.

![Diagram of management planning framework](image-url)
1.4. CLLAMMecology research components

The CLLAMMecology research program had three linked components and three sub-components (Figure 1.3). Together, these provided the building blocks for the ecosystem framework, which were:

- The development of a hydrodynamic model of the Coorong and Murray Mouth suitable for use in longer-term (30–100 years) forecasting of changes in the water level and salinity regimes.
- A field program to study the ecology of key species of invertebrates, fish and waterbirds and to quantify key ecological processes, such as nutrient cycling and food web structure.
- The development of ecological models to predict the distribution of key species, habitats, and of alternative ecosystem states as a function of water level, salinity, and other environmental drivers.

![Figure 1.3](image)

*Figure 1.3.* The CLLAMMecology research program structure was organised around three interlinked components: *Coorong Hydrodynamics, Ecosystem Responses* and *Coorong Futures*. Three subcomponent (or “themes”) informed the *Ecosystem Responses* component: In Key Species Responses, the distribution and behaviour of a range of organisms (invertebrates, *Ruppia* seagrass, fish and birds) was studied as a function of changes in environmental conditions (in particular the water level and salinity regimes). *Sustaining Food Webs* focused on developing an understanding of food webs and creating models that could be used to investigate the effects of river flows on ecosystem productivity. *Dynamic Habitat Mapping* aimed to describe how the distribution of habitats, such as mudflats, would change under different management conditions. *Coorong Futures* developed ecological models based in part from information collected in this study and, using these ecological models, evaluated 20 potential future climate and management scenarios for the Coorong.

To illustrate how the framework can be used, in a fourth component to CLLAMMecology, 20 longer-term climate change and management scenarios for the Coorong and Murray Mouth region were investigated for their potential ecological outcomes.

The field program occurred during a period (late 2006 to 2008) when there was no freshwater inflow from the Lower Lakes barrages to the Coorong and Murray Mouth (Figure 1.4). This provided a unique opportunity to learn about the ecology of this system under extreme environmental conditions. Historical water quality and ecological information from periods when River Murray flows occurred were also used to develop the ecological models.
1.5. Study design

Research was conducted at 12 focal sites along the salinity gradient. These include three sites to the north of, or around the Murray Mouth channel (Goolwa Channel, Mundoo Channel and Barkers Knoll), six sites in the North Lagoon (Ewe Island, Pelican Point, Mark Point, Long Point, Noonameena and Parnka Point) and three sites in the South Lagoon (Villa dei Yumpa, Jack Point and Salt Creek). Having a consistent set of sites ensured that findings from the various research activities could be integrated and compared, although not all sites were used for all investigations undertaken.

1.6. Report structure

The key highlights of the CLLAMMecology research program are presented in this report in sections summarising the results of individual research topics:

- Hydrodynamics of the Coorong
- Dynamic habitat
- Role of Lower Lakes in modifying the nutrient supply to the Coorong
- Nutrient cycling and primary production in the Coorong
- Key species responses
- Coorong food webs
- Ecosystem state models of the Coorong
- Scenario analyses.
2. Hydrodynamics of the Coorong

Reduced river flows and the associated increased likelihood of Mouth closure threaten the ecological function of the Coorong through the tendency for higher salinities in the system, alterations to the water level regime, and blockage of fish migration pathways. Water level is a key environmental attribute that determines the availability of physical habitat for birds and other aquatic life. Similarly, all aquatic organisms have tolerance limits to salinity levels and their variation, so the salinity regime within the Coorong is a major determinant of where and how well such organisms can exist. The hydrodynamics of the Coorong is the study of how water levels and salinity behave the way they do and how they might be altered by intervention such as Mouth dredging and increases or decreases in the flows through the barrages. Hydrodynamic features of the Coorong summarised in the following section are described in greater detail in reports by Geddes and Hall (1990) and Webster (2005, 2007).

The key elements of the Coorong hydrodynamics are the Mouth channel connecting the Coorong to the sea, the North and South Lagoons, which are relatively deep and wide, and the channel at Parnka Point connecting the two lagoons, which is shallow and narrow (Figure 2.1).

![Diagram of Coorong hydrodynamics](image)

**Figure 2.1.** Schematic of major basins, connecting channels, and barrage flows in the Coorong. Not to scale.

Water level variations within the Coorong are caused by a series of factors including sea level changes, the winds, and flows through the barrages. Sea level varies seasonally with highest levels occurring in winter and lowest levels occurring in autumn (Figure 2.2). This seasonal variation causes water levels to vary along the length of the Coorong. When there are significant barrage discharges, the constriction of the Mouth channel causes water to back up within the Coorong contributing to the maintenance of elevated water levels into spring.

Tides do not spread very far along the Coorong, but are an important cause of currents near the Mouth. Wind blowing on the water surface pushes water in the downwind direction. This causes the water to pile up against the downwind shore and results in an upwards tilt of the water surface from the upwind to the downwind end to raise water levels there. The system relaxes when the wind speed drops, and then currents flow along the Coorong in the opposite direction.

Salinity measurements in the Coorong have shown enormous variability over the last decades, primarily due to variation in barrage flows. The South Lagoon always has higher salinities than the North Lagoon (Figure 2.3). During November 1975, salinities in the South Lagoon were similar to those of seawater, whereas salinities in the North Lagoon were mostly much less than a quarter of those of seawater (Geddes 1987). This was a time of very large barrage flows – the years 1974 and 1975 averaged barrage flows of ~46 GL/day. Barrage flows in the last few years have been small (~1 GL/day between 2001–2007) and salinities in both lagoons have been much higher than normal. In 2007–2008, salinity in the South Lagoon has been measured to exceed that of seawater by a factor of four or more.
Figure 2.2. Measured monthly water levels at Goolwa in the North Lagoon and at Victor Harbor on the sea about 20 km from the Mouth averaged over the years shown in the legend. Average monthly discharges through the barrages are also shown.

Figure 2.3. Longitudinal profiles of salinity (salinity gradient) measured along the Coorong on December 9 1999 and on December 8 2004. Data were provided by the South Australian departments for Environment and Heritage, and of Water, Land and Biodiversity Conservation.
How barrage flows affect salinity in the Coorong can be demonstrated with a conceptual model of the system (Figure 2.4). The top panel shows the water motions in the Coorong. Evaporation from the water surface of both lagoons continuously draws in seawater through the Mouth on the left side of the schematic. This causes an advective current through both lagoons from left to right. Oscillatory water motions occur in both lagoons as a result of sea level changes that come through the Mouth and also due to wind acting on the water surface. The bottom panel shows the consequent average salt balance. The flow of seawater through the Mouth carries salt into the system and this is transported into the South Lagoon by the advective flow. This flow tends to cause salt accumulation in the inner sections of the Coorong. However, the oscillatory flows mix the saline water back towards the Mouth so that the system is balanced when the advective transport of salt into the Coorong matches the mixing transport in the opposite direction.

**Figure 2.4.** Conceptual model of water motions and salt balance in the Coorong. The balance between the input of salt by advection and the export by long channel mixing gives rise to the Coorong salinity gradient. This conceptual model applies in an average sense with seasonal variation in sea levels, evaporation rates and winds.

Barrage flows affect Coorong salinities in three ways. First, significant barrage flows clear the Mouth channel of accumulated sand. A deep Mouth channel allows the efficient circulation of sea level fluctuations into the Coorong. This important cause of the oscillatory flows mix accumulating salt back towards the sea. Secondly, the barrage flows, which typically occur in spring (Figure 2.2) reduce salinity in the Coorong channel and in the seaward end of the North Lagoon to values much less than seawater. Consequently, the advective flow through the Coorong to replace evaporative losses has a lower salinity than seawater and so transports less salt into the system. Finally, the raising and lowering of water levels when the barrage flows rise and subside causes water to push into and out of the Coorong contributing to long-channel mixing.

A computer model was developed to simulate water levels, salinity, and currents within the North and South Lagoons of the Coorong. These respond to water level changes in the sea, flows through the barrages, wind, evaporation, precipitation, and flows into the south end of the South Lagoon from the USED scheme (Webster 2007). The hydrodynamic model will indicate how the Coorong will respond to input flows and the forces acting on it as well as provide a tool to assess the likely effectiveness of management interventions. The output from the model can be readily used to the drive different species, habitat and ecosystem models developed during CLLAMMecology.
3. The Dynamic Habitat

The diversity of habitats located within a small geographical area makes the Coorong unique. This diversity is determined in particular, by the salinity gradient, which under natural conditions ranges from almost fresh to estuarine through to hypersaline. Understanding the distribution, spatial extent and connectivity of these habitats is crucial for successful conservation and management of the region. These factors were studied in the Dynamic Habitat Mapping theme of CLLAMMecology (Sharma et al. 2009).

3.1. Regional habitat maps

Comprehensive maps were developed of a variety of habitats and habitat attributes describing the Coorong as it was in the early to mid 2000s. This mapping included surrounding vegetation assemblages and wetlands, and attributes such as subtidal sediment characteristics and bathymetry. A variety of data sources were used in the mapping process including pre-existing mapping conducted by the South Australian Department for Environment and Heritage, aerial photography, satellite imagery, in situ field surveys of benthic habitats and sediments, and topographic surveys. Field sampling focused on the 12 CLLAMMecology focal sites studied by the broader research team. This sampling informed detailed habitat maps of a ~2 km wide area extending across the lagoon from the eastern to the western shore. Mapping efforts based on existing data sources and remote sensing were also incorporated into maps of the entire Coorong and its surrounds.

At a broad scale, 5,755 ha were mapped using remote sensing, with about half the mapped area in the lagoons (49.9%), 34.7% on the peninsula, 13% on the mainland, and less than 3% on islands. Twenty-four wetland and 14 terrestrial habitat types were recorded from the reference sites (see Figure 3.1 for the map of Pelican Point as an example). The Coorong and surrounding region were classified into ten broad habitat categories including agricultural and pastoral land. The habitat maps generated through the current study provide a reference of the available habitats in the area, and baseline information for making future predictions on habitat distribution based on the major ecological drivers of the system: water level and salinity. The maps also inform estimations of the likely occurrence of species or ecosystems in the region, and can be used to help determine the likely ecological effects of management decisions on water flow over the barrages.

3.2. Coorong Digital Elevation Model

The topography and bathymetry of the Coorong region had to be determined precisely to develop accurate habitat maps. A range of data sources were combined with predictive modelling to develop an accurate and comprehensive Digital Elevation Model (DEM) of the Coorong and surrounds. While a relatively good data set on bathymetry is available from the South Australian Water Corporation for the North Lagoon, and there is an existing DEM for terrestrial areas of South Australia, including the area surrounding the Coorong, there is limited bathymetric data available for the South Lagoon. The few field data on depth in the South Lagoon were used to develop a predictive model of bathymetry using remotely sensed data to generate a comprehensive bathymetry (Figure 3.2), although the predictive ability of the model was poor for regions south of Jack Point, where turbidity was high. This data and the bathymetry data from the North Lagoon, as well as the SA regional DEM, were then merged into a seamless DEM of bathymetry and topography for the Coorong, allowing prediction of lagoon volumes and the extent of different habitats based on depth at different water levels.
3.3. Benthic habitat

Sediment maps were generated for the entire Coorong. Sediment characteristics were obtained at a number of points at each field sampling site. Modelling was then used to predict characteristics over each reference site, based on distance from the Murray Mouth, underwater topography, distance to shore, and salinity, amongst other variables. Three main depositional areas were found along the Coorong where sediments are fine and organically-enriched: (1) the middle channel of the lagoons, (2) the constriction between the North and South Lagoons, and (3) the western (seaward) shore of the North Lagoon, particularly south of Long Point.
3.4. Mudflats

The internationally recognised status of the Coorong wetlands as migratory bird habitat has been largely due to the opportunities they provide for large numbers of birds to feed in a highly productive estuarine and lagoonal environment. A significant proportion of this foraging occurs on the large tracts of mudflats found throughout the Coorong. The productivity of the mudflats varies along the length of the Coorong, depending on water quality (particularly salinity), nutrient inputs, sedimentary structure, and the duration, frequency and extent of inundation. Resident macroinvertebrate populations and aquatic vegetation such as _Ruppia_ species are indicators of mudflat productivity and a food source for fish and birds.

High resolution topographic/bathymetric models for the 12 CLLAMMecology reference sites (e.g. Figure 3.3), confirm the importance of the South Lagoon mudflats, which are crucial...
foraging grounds for many waterbirds. It contains some 61% of available mudflat, as measured in the reference sites. All mudflats should be highly productive if the necessary physical, chemical and biological conditions exist. Across all 12 reference sites the 0 m to 0.5 m AHD elevation range is most important as it contains approximately 43% of all available mudflat area. The second most important elevation class is -0.5 m to 0 m AHD, containing approximately 40% of total available mudflat area. By combining the hydrodynamic model, the Coorong DEM and the sediment distribution map, it is now possible to define the distribution of mudflats with particular inundation regimes and sediment textures. These are important factors in the distribution of benthic invertebrates (an important food source for fish and birds) in the Coorong (see the summary for the distribution of benthic invertebrates in Section 6).

Figure 3.3. High resolution bathymetry for Pelican Point.

3.5. Dynamic habitat modelling

The bathymetry data were combined with the hydrodynamic model and ecological information (such as salinity tolerance) collected in the Key Species theme (see section 6), to develop dynamic GIS habitat models for key bird and fish species (Sharma et al. 2009). First, a generic model to predict the potential habitat for shorebirds was developed by predicting the location and extent of mudflats. For the purpose of the model, mudflats were defined as soft sediment areas that are either immersed or covered by no more than 12 cm of water, where most shorebird foraging occurs. Mudflat availability varied spatially and temporally along the Coorong, and is influenced by tide, wind, rainfall and evaporation, some of which are dependent on the distance from the Murray Mouth and are affected by seasonal variation. The modelling of mudflats at different water levels suggests that an average water level of 0.12 m AHD gives the maximum average mudflat area in the three reference sites examined in detail (Barker Knoll, Noonameena and Salt Creek), with the majority of the mudflats located on the eastern shores (Figure 3.4). Further development of the waterbird habitat models could be made by including information specific to different species, including the potential distribution of their favourite food sources.

Habitat models for key fish species were derived based on their salinity tolerance. Four out of seven key fish species examined demonstrated a significant relationship with salinity. These species were Yelloweye Mullet *Aldrichetta fosteri*, Smallmouth Hardyhead *Atherinosoma microstoma*, Greenback Flounder *Rhombosolea taprina* and Tamar River Goby *Afurcagobius*
Among the three different salinity gradient scenarios examined along the lagoon, a salinity range from 5 to 90 g L$^{-1}$ was found to be the best for these four key species, as well as for supporting other important biological communities including macrophytes and infauna. The extent of habitat available for each of these fish species depends on the salinity gradient at the time, which varies considerably over time (see Figure 3.5 for Yelloweye Mullet).

Figure 3.4. An example of a mudflat availability map generated by the GIS-based model at Barker Knoll (January 8, 1988 at 9:00 AM).

3.6. Potential applications for the design of Coorong environmental flow strategies

The Dynamic Habitat theme of CLLAMMecology has developed a set of tools that will help managers design better intervention strategies for the rehabilitation of the Coorong region. For the first time, these tools allow managers to explicitly incorporate spatial considerations in the design of environmental flow strategies for the Coorong, such as where mudflats with a particular inundation regime will be located under different management interventions.

Similarly, it is now possible to quantify the habitat that could be gained or lost under different management interventions for a range of key waterbird and estuarine fish species. The collation and synthesis of a large amount of spatial information about the Coorong region is an important legacy of the program. This information can be used for a variety of other purposes in addition to the design of environmental flow strategies.
Figure 3.5. Habitat prediction for Yelloweye Mullet in July 1976, July 1988 and January 2005. GC = Goolwa Channel; MC = Mundoo Channel; BK = Barker Knoll; EI = Ewe Island; PP = Pelican Point; MP = Mark Point; LP = Long Point; NM = Noonameena; PA = Parnka Point; VY = Villa dei Yumpa; JP = Jack Point and SC = Salt Creek.
4. Role of the Lower Lakes in Modifying the Nutrient Supply to the Coorong

Lakes transform nutrients and organic material and in doing so influence the productivity of downstream ecosystems. As a component of the Sustaining Food Webs theme, an historical nutrient budget developed for the Lower Lakes found they were consistently a sink for phosphorus, nitrate-nitrite and silicon, but an overall source of organic forms of nitrogen (Figure 4.1, Cook et al., 2008). The Lower Lakes are a significant modulator of material entering the Coorong, increasing the nitrogen to phosphorus ratio of material. Upon flow into the Coorong this is likely to stimulate productivity since coastal waters are generally considered to be limited by nitrogen. In addition, the lakes converted inorganic nutrients into organic forms and so the increased productivity is likely to be initially observed in zooplankton or bacterial communities.

![Nutrient Budget Diagram](Image)

**Figure 4.1.** Nitrogen and phosphorus budget for the Lower Lakes, 1979-1996. Units are kmol over the period. The Lower Lakes control nutrient and organic matter input from the River Murray to the Coorong and Murray Mouth.

Water levels in the Lower Lakes fell to unprecedented levels over the course of this study, as a result of the extensive diversions and severe rainfall deficiency in the Murray-Darling Basin. This had a major impact upon physical and chemical conditions within the Lower Lakes.

Salinity increased with falling water levels in the lakes (Aldridge et al., 2009). Initially, the increase in salinity in Lake Alexandrina appeared to be mainly by leakage through the barrages (Figure 4.2a). This resulted in a strong horizontal salinity gradient across the lakes and in a permanent vertical density stratification in areas such as Goolwa Channel. This vertical density stratification, where the denser saline water at the bottom did not mix with the overlying freshwater, resulted in oxygen depletion of the hypolimnion (bottom waters) in areas close to the barrages (Figure 4.2b). In addition, soluble nutrient concentrations increased, with concentrations found to be higher close to the barrages, particularly in the hypolimnion. This reflected a change from aerobic to anaerobic nutrient cycling processes within the Lower Lakes.
Figure 4.2. Salt intrusions (A) and depletion of dissolved oxygen of the hypolimnion (B) near Goolwa Barrage.

Lower water levels, increased salinity and oxygen depletion of the hypolimnion reduced the habitable area within the Lower Lakes for freshwater organisms. In addition, increased suspended solid loads were observed, which is likely to reduce primary productivity and further reduce habitat and food for higher organisms. The increased suspended solid concentrations were thought to be a result of the finer sediments that have accumulated towards the middle of the lake. Finer sediments, which require less energy to be resuspended, have been exposed to wave energy as water levels have fallen and resuspended into the water column. The movement and storage of sediments in the Lower Lakes will be very sensitive to changes in their water level regime because they are shallow.

Sediment incubation experiments undertaken during the study also shed some light on the potential impact of drying and reflooding sediments on nutrient cycling in the lakes. Drying-reflooding cycles increased the flux of soluble phosphorus from the water column to the sediment. In comparison, there was a large flux of soluble nitrogen from the sediments to the water column (Figure 4.3). Reflooding of exposed lake sediments could generate a nitrogen pulse in surface water in the short-term.

This study highlighted the role of the water level and salinity regimes as key ecosystem drivers for the Lower Lakes. Water level and salinity control many important physical processes in the lakes, such as density stratification, the distribution of sediments, the cycling of nutrients and the distribution of organisms.
Figure 4.3. Flux of ammonia-nitrogen in permanently wet and dried-reflooded sediments of Site 1 (fine sediment) and 2 (coarse sediment). Positive and negative values denote flux from sediment to water column and from water column to sediments, respectively. Water level variations have a strong impact on the recycling of nutrients from Lower Lakes sediments.
5. Nutrient Cycling and Primary Production in the Coorong

Aquatic plants in the Coorong range from microscopic phytoplankton (microalgae) to larger plants such as the aquatic grass *Ruppia tuberosa*. The quantity and type of organic matter embodied in the plants determines the structure of the Coorong food chains and constrains the abundance and species composition of the fish, bird and higher organisms that feed there. There is a tight nexus between plant production and the availability of specific nutrients (principally nitrogen and phosphorus). This little studied area has been the focus of the biogeochemistry and primary production investigations in the *Sustaining Food Webs* theme, and the major results are summarised here. Organic matter production is discussed first, followed by an outline of nutrient transportation and cycling results.

5.1. Current organic matter production

Microalgae were the main producers of organic matter in the Coorong during the study period. Algal biomass in the water column, as measured by chlorophyll *a* concentration, increases along the Coorong salinity gradient reaching quite elevated concentrations in the South Lagoon. Algal biomass was higher in this location in winter compared to summer. The microphytobenthos (the assemblage of algae and other microorganisms) on the surface of the sediment in shallow margins of the Coorong were the only other major producers of organic matter. Measurements of primary production rates using different techniques (Haese *et al.* 2009, Nayar and Loo 2009) indicated that benthic primary production rates were greater than pelagic primary production rates; these rates were higher in the South Lagoon than in the North Lagoon. This was not unexpected because the shallow depth of the Coorong allows light to reach the bottom at most locations. A detailed analysis (Revill *et al.* 2009) of the pigments characteristic of different algal classes showed that algal diversity was low throughout the Coorong. Green algae dominated in the water column, while the sediment organic matter production was almost exclusively by diatoms (silica-containing algae). Primary production in the water column was higher in the South Lagoon in winter. In summer the relative contributions reverse, but are generally lower. Cyanobacteria were more abundant in the South Lagoon in summer and this suggests that primary production there may be nitrogen limited in this season.

5.2. Organic matter production in the recent past

In addition to algal pigments, the project applied other techniques (including lipid biomarkers, stable carbon isotopes and $^{13}$C NMR spectra; Figure 5.1) to characterise the organic matter in Coorong sediments. Results showed that despite the apparent high benthic and pelagic primary production rates, only organic matter of benthic origin was stored in the surficial sediments and thus available as food supply for higher organisms. Sediment cores were used to look at changes in the origins of organic matter over time in the Coorong. The full spectrum of techniques were applied in one study (Krull *et al.* 2008; Krull *et al.* 2009) to reveal that prior to European settlement, *Ruppia* species was a much more important source of organic matter in the North Lagoon compared to now. This is a major difference from the present algal-dominated system and points to a substantially different historic food web structure.
Figure 5.1. $^{13}$C NMR spectra of recent Coorong sediments (bottom) together with the spectra of potential sources of organic matter in the North Lagoon. Each peak in a spectrum represents the abundance of a particular chemical functional groups in the organic matter. This shows that under current conditions most of the sediment organic matter is derived from algae (the main organisms in phytoplankton, for example). A similar analysis of older sediments suggested that *Ruppia* made a more important contribution to the organic matter pool prior to 1950.

5.3. **Nutrients in the Coorong**

Total concentrations of the macronutrients (nitrogen and phosphorus) critical for algal production varied markedly along the length of the Coorong and reached a maximum in the South Lagoon (Figure 5.2). Concentrations there were higher in the summer than in the winter due to evaporation. Each nutrient exists in a variety of different chemical forms. In the Coorong, the principal nutrients are mostly in non-biologically available forms. Thus, despite high apparent nutrient concentrations, plant production in the Coorong is probably nutrient limited, especially by nitrogen, for most of the time. The formation and dissolution of minerals (such as carbonates) along the salinity gradient could also exert a strong geochemical control on the availability of phosphorus (Ford 2007; Fernandes and Tanner 2009). Groundwater seeps in the South Lagoon contribute a significant amount of biologically available N to the ecosystem at times of low river inflows (Haese *et al.* 2009).
Figure 5.2. Variation in average nutrient concentrations along the Coorong in barrage high flow years (1998–2001) and low/no flow years (2002–2007) (top: Nitrogen-containing species; lower: Phosphorus-containing species). Vertical dotted line marks the boundary between North and South Lagoons. Dissolved organic nitrogen (considered not readily bioavailable to support algal growth) is higher in the South Lagoon in no-flow years due to evaporation. Biologically available ammonia (grey bars top graphs) is noticeably and uniformly higher in the South Lagoon relative to the North Lagoon, in no-flow years.

5.4. Nutrient imports and exports

Mathematical techniques were developed for constructing nutrient budgets for the Coorong from an extensive monitoring dataset (Grigg et al. 2009). These showed that while much of the riverine nutrient input goes directly to the sea, some bioavailable nutrients are retained in the North Lagoon, and they are subsequently released and redistributed to the South Lagoon over time (Figure 5.3). This effect can last for several years after a flood. In contrast, at times of low River Murray inflows over the barrages, the estuarine area near the Murray Mouth can be a net source of bio-available nutrients, probably by microbial breakdown of organic matter in the sediments deposited during high barrage flows.

This study has demonstrated that the Coorong has a number of unusual and unique biogeochemical features owing to its particular hydrodynamic regime and extreme salinity gradient. Inflows from the River Murray from the Lower Lakes barrages have a strong impact on biogeochemical processes in the Coorong by bringing large amounts of new nutrients into the system, which are used in subsequent non-flow years; by changing salinity, and by promoting the exchange of nutrients between lagoons. These processes modulate the quantity and types of organic matter produced in the Coorong and thus markedly influence the ecosystem structure.
The past contribution of *Ruppia* species in the Coorong ecosystem primary production remains a knowledge gap. This aspect could not be investigated in this study due to the current limited distribution and density of *Ruppia* (see section 6).

**Figure 5.3.** Average fluxes of total nitrogen (TN) and total phosphorus (TP) between the ocean, Murray Mouth area, River Murray and the North and South Lagoon area for high barrage flows (1998–2001) and low flows (2002–2007) calculated from modelled hydrodynamic exchanges and field nutrient concentration measurements. The horizontal arrows indicate the direction of net transport (blue: flow years; brown: no/low flow years) between the different compartments. The vertical arrows within each compartment (blue: high flow; brown: no/low flow) indicate net nutrient release (arrow up) from sediments, arrow down indicates net deposition within the compartment and the values in brackets are the range in the standing stock of TN or TP in the water column. These results underline the connectedness between the three compartments, and the greater role of high flows relative to low flows in the net delivery of TN to the whole system. The modelled net flux of TN in the South Lagoon under low flow conditions may be a result of the ammonia-rich groundwater inflows observed during field investigations. (units: tonnes/yr).
6. Key Species Responses

6.1. Background

When CLLAMMecology was conceived in 2005, the collaborative work was to focus on assessing the ecological responses, and hence benefits, of providing different volumes of environmental water to the Coorong region. The Key Species component of CLLAMMecology proposed to document the responses of selected species to changes in their environments likely under different management regimes for the region, particularly quantities and timing of River Murray water releases over the barrages. Key species were selected based on their conservation, economic or ecological significance. The intention was to produce robust response models for signature plants, invertebrates, fish and birds. The models would focus on critical life history stages and address recruitment processes and the performance of key species or functional groups, and how these related to prevailing flow and water quality conditions. Documenting physiological and/or behavioural responses including movements would show how key species coped with environmental changes. Key physical variables that change with water regime are water level, nutrients, salinity, turbidity and temperature. The seasonal timing, extent or duration of a changed condition, and the rate of change in condition, are other key components.

The primary strategy was to exploit the marked salinity gradient along the length of the Coorong and to document the distribution, abundance and performance of key species both spatially and temporally before and after releases of freshwater. Since the conditions at any one location were likely to change and change to different extents, this allowed a powerful in situ (on site, i.e., field-based) database to be developed for use in model development. In situ measurements include the added effects of biotic interactions on performance (competition, predation) and are consequently more valuable for making predictions from different water regimes than ex situ (off site, i.e., laboratory-based) studies. Some field-based and laboratory-based experimental manipulations were also undertaken to investigate responses to particular environmental variables for a few species that were amenable to such manipulations. Available longer-term datasets were incorporated into the databases to provide a stronger basis on which to model responses.

No environmental flows reached the Coorong during the last three years. Consequently, the Key Species component of CLLAMMecology assessed the continuing response of the Coorong’s biota to no-flow conditions. No environmental flows of water are likely to reach the Coorong for at least another two years given the current low storage, low inflows of water into the Murray-Darling system and the historically low water levels in the Lower Lakes. Understanding how the biota copes with these no flow conditions is critically important for informing debate about adequate environmental flows to the region in the future. Summaries of the responses of a key aquatic angiosperm *Ruppia tuberosa*, benthic invertebrates (particularly polychaetes), fish and birds to no environmental flow conditions are presented below.

6.2. Changes in the distribution and abundance of *Ruppia tuberosa*

*Ruppia tuberosa* plays a central role in the Coorong’s ecology. It provides a food source for waterbirds and habitat for invertebrates and fish (Rogers and Paton 2009a). In recent history, *Ruppia* spatially dominated the submerged aquatic vegetation of the South Lagoon and the southernmost 5-8km of the North Lagoon. The distribution, abundance and performance of *Ruppia* in the South Lagoon have been monitored annually since 1998. This monitoring involved assessing the cover and density of shoots in winter as well as the abundance of propagules (seeds and turions) in summer and winter. Monitoring was conducted at four sites in the South Lagoon where *Ruppia* had been prominent since 1984–5, and at one site in the North Lagoon (Noonameena) where *Ruppia* had not been detected. Winter shoot cover and density have both declined across the South Lagoon since 1999, and no shoots were recorded from any of the four sites in 2008. The nature of these declines was also spatially explicit, with declines in cover being more temporally advanced in the south than the north of the South
Lagoon. This suggests a range contraction from south to north for *Ruppia* in the South Lagoon. Conversely, *Ruppia* shoots were recorded further north in the North Lagoon at Noonameena from 2005 onwards, indicating that *Ruppia* was slowly increasing in distribution and abundance in the North Lagoon.

Measures of propagule abundance showed similar spatiotemporal patterns, with the propagule banks declining over time in the South Lagoon. Propagule banks consisted of seeds and turions, with turions accounting for 47–82% of all propagules in January from 2001–2006, but only 15% and 3% in 2007 and 2008, respectively. This is consistent with the short-lived nature of turions. At present, *Ruppia* plants appear unable to establish from the current seed-dominated propagule banks in the South Lagoon, possibly because many of the seeds are not viable or are buried too deep. Turions appear more important than seeds for dispersal, since turions and not seeds, were detected at sites like Noonameena up to six months before the first shoots were detected. Further work is required on the composition and dynamics of *Ruppia* propagule banks in the Coorong.

In July 2008, the distribution of *Ruppia* was determined at a finer scale (every ~3 km) using recent historic distributions as a guide. This survey confirmed the absence of *Ruppia* plants from the South Lagoon, with the southernmost records of shoots coming from Parnka Point at the junction of the North and South Lagoons. In July 2008, the highest densities of *Ruppia* shoots were found between ‘The Needles’ (~6 km north of Parnka Point) and Noonameena (~21 km north of Parnka Point). Shoots were also recorded at very low densities at Long Point, ~31 km north of Parnka Point, suggesting the continued range expansion of this species into the North Lagoon.

Preliminary analyses of the hydrological drivers for these historic changes were based on the hydrological models of Webster (2005), and used a statistical technique called Nonparametric Multiplicative Regression (NPMR). The best candidate model using this technique, \((xR^2 = 0.637)\), found that a combination of three salinity variables and one generic water level variable best explained changes in the distribution of *Ruppia* in the Coorong. However, when these results were compared with the current distribution of *Ruppia*, the model failed to predict the rapid northern expansion of the species into the North Lagoon, although the South Lagoon decline was well predicted.

A more robust modelling approach is required to accurately predict the responses of this species to future Coorong environments given the significant role of *Ruppia* in the Coorong ecosystem and its predicted sensitivity to hydrological changes. While the regression techniques used in the initial models may continue to prove useful, they are correlative and not causative. Future work should document the responses of *Ruppia* to its physical (hydrological) and biotic environment and incorporate these responses directly into the models.

### 6.3. Changes in distribution, abundance and performance of benthic macroinvertebrates

Distinct adult and juvenile macrobenthic communities were present in the Murray Mouth region, the North Lagoon and the South Lagoon of the Coorong, and these did not change significantly between December 2006 and October 2007 (Rolston and Dittmann 2009). The abundances and diversity of both adult and juvenile macrobenthos decreased with distance into the North and South Lagoons. Salinity was the driving environmental variable found to best explain the distribution of both adult and juvenile macrobenthos. Sediment organic content was also an important variable.

Adult and juvenile macrobenthic diversities and abundances were greatest in the Murray Mouth region were salinities were typically marine, before decreasing in the North Lagoon with increasing salinity. In the Murray Mouth region macrobenthic abundances were dominated by Polychaeta (particularly *Capitella* species), Amphipoda and the micro-bivalve *Arthritica helmsi* (Figure 6.1). This contrasted with the South Lagoon findings where salinities were typically above 120 g/L. Only insect larvae were present in the South Lagoon in December 2006, and no taxa were present in January and March 2007. The greatest abundances of both adult and
juvenile macrobenthos occurred at Pelican Point within the Murray Mouth region. This site was also distinct from other sites in terms of sediment grain size.

The juvenile macrobenthic fauna were dominated by four species: the polychaete worms *Capitella* species and *Simplisetia aequisetis*, the micro-bivalve *Arthritica helmsi* and the larvae of the chironomid *Tanytarsus barbitarsus*. Juveniles of each of the four dominant species were present in the system throughout the year, while less common species such as the polychaetes *Boccardiella limnicola* and *Nephtys australiensis* showed more seasonal abundances.

Macrobenthic abundances decreased significantly at high mudflat exposures in the Murray Mouth region, and at high and medium exposures in the North Lagoon region. Experimental translocations of macroinvertebrate fauna in sediment from areas of high salinity to lower salinity, and from areas of high mudflat exposure to low exposure led to an increase in species diversity and abundance. The converse was true for the reciprocal translocations where macrobenthic invertebrates were unable to survive in exposed sediment beyond a week. Thus the distribution and abundance of the macrobenthos will be restricted to areas that are either permanently covered or regularly inundated with water (tidal areas). This pattern of reduced abundance on exposed or partially exposed mudflats may explain the reduction in foraging performances of the small calidrine waders with distance from the waterline. Salinity was the other key variable driving the distribution, abundance and performance of the macrobenthos.

Under the current conditions of no environmental flows the distribution of key components of the macrobenthos (e.g. Polychaeta) will be restricted to the Murray Mouth region and the upper 10 km of the North Lagoon where salinities currently remain suitable. Based on translocation results, reductions in salinity due to the provision of an environmental flow are likely to increase the distribution and abundances of the macrobenthos within the Murray Mouth region and northern Coorong. What is not known is how the macrobenthos will continue to fair with the ongoing absence of an environmental flow to this region.

### 6.4. Changes in the distribution and abundance of fish

A fine-mesh seine net was used to collect fish from ten sites: five located in the Murray Mouth subregion, three in the North Lagoon and two in the South Lagoon. Sampling was conducted approximately every three months between October 2006 and September 2008. A sinking composite gill net was used to catch fish at four of these sites (two each within the Murray Mouth and North Lagoon; Noell *et al*. 2009).

A total of 66,515 fish representing 26 species were caught using the seine net, many of which were either small-bodied fish or juveniles of larger species (Figure 6.2). A general decline in species diversity occurred with increasing distance from the Mouth. All 26 species were found in the Murray Mouth subregion; 13 in the North Lagoon; while only 1 species, the Smallmouth Hardhead *Atherinosoma microstoma*, was found in the South Lagoon. *Atherinosoma microstoma* was by far the most abundant species in the current study, contributing 61% to the total number of fish collected. The next two abundant species were Yelloweye Mullet *Aldrichetta forsteri* (17%) and Sandy Sprat *Hyperlophus vittatus* (16%). In the Murray Mouth subregion, *Hyperlophus vittatus* (38%) and *Aldrichetta forsteri* (35%) were the most abundant species, followed by *Atherinosoma microstoma* (10%), Australian Salmon *Arripis truttaceus* (7%), and Common Galaxias *Galaxias maculatus* (3%). In the North Lagoon, the vast majority of fish were *Atherinosoma microstoma* (92%), with relatively small contributions by *Aldrichetta forsteri* (5%) and *Hyperlophus vittatus* (2%). The Murray Mouth had greater species diversity although more fish were caught in the North Lagoon, mainly due to the very high abundance of *Atherinosoma microstoma*. This species accounted for 89% of all individuals collected from the North Lagoon.
Figure 6.1. Abundance (individuals m\(^{-2}\), mean ± standard error) of four key species (A = *Capitella*; B = *Simplisetia*; C = *Nephtys*; D = *Arthritica*) present along the Coorong salinity gradient over the three sampling times (Dec 2006, Jan 2007 and March 2007). See Figure 1.1 for site location (with site 1 corresponding to Goolwa Channel in the Murray Mouth and site 12 corresponding Salt Creek in the South Lagoon). At the time of the study, the highest diversity and density in benthic macroinvertebrates was in the Murray Mouth area.
Figure 6.2. Mean number of fish species and density of fish (± 1 standard error) derived from seine net samples collected at sites in order of increasing salinity in the Murray Mouth (M), North Lagoon (N) and South Lagoon (S) between October 2006 and September 2008, including the densities of the four more abundant species: Smallmouth Hardyhead *Atherinosoma microstoma*, Yelloweye Mullet *Aldrichetta fosteri*, Sandy Sprat *Hyperlophus vittatus* and Australian Salmon *Arripis truttaceus* (Noell et al. 2009). Smallmouth Hardyhead is the most abundant and salt-tolerant fish in the Coorong and a key prey for larger predatory fish and piscivorous waterbirds.

The gill net method yielded a total catch of 2,679 fish representing 16 species. Thirteen species were found in each of the Murray Mouth and North Lagoon subregions. The three most abundant species (overall and in each subregion) caught using this method were *Arripis truttaceus* (42%), *Aldrichetta fosteri* (37%), and Mulloway *Argyrosomus hololepidotus* (15%), making up 94% of the total catch from both subregions. *Arripis truttaceus* made a significant contribution to the number of fish in the Murray Mouth (61%), and *Aldrichetta fosteri* was most common in the North Lagoon (68%).

Classification and ordination of the 100 seine net samples (10 sites × 10 sampling occasions) by multivariate analysis demonstrated that fish assemblages tended to be more similar between sites within the same subregion or proximate to one another. Further, the greatest dissimilarity occurred between the typically multi-species assemblages of the Murray Mouth subregion and the zero or single-species samples of the South Lagoon. Assemblages in the North Lagoon were intermediate, usually comprising more than one species but fewer species than in the Murray Mouth assemblages. Significant differences were found between assemblages of
different subregions and these were generally attributed to dissimilarities in abundances of *Atherinosoma microstoma*, *Aldrichetta forsteri*, *Arripsis truttaceus* and *Hyperlophus vittatus*. A smaller, yet still significant difference was also found between assemblages of the Murray Mouth and North Lagoon from gill net samples. This was attributed to relatively fewer *Arripsis truttaceus* and *Argyrosomus hololepidotus* and greater numbers of *Aldrichetta forsteri* in the North Lagoon. No temporal differences (by year or season) were found between assemblages for either seine or gill net samples, possibly indicating stability of the regional fish fauna during the current drought.

All 12 species known to complete their life cycle within the region (i.e. estuarine species) were collected among the grand total of 31 species from both seine and gill net samples. Six of these 31 species had not been recorded in previous inventories for the region. Each of these additional species is believed to be of marine origin, either marine estuarine-opportunist or stragglers.

The lack of freshwater input, along with drought conditions, has resulted in higher salinities throughout the region (probably the highest ever), with some parts extremely hypersaline. A strong north-south salinity gradient that increases with distance from the Murray Mouth persisted throughout the study, with mean salinities of 30–40 g/L in the Murray Mouth subregion, 61–86 g/L in the North Lagoon, and 105–164 g/L in the South Lagoon recorded over the sampling period.

Among several water quality variables, salinity alone was the best explanatory variable for the observed fish assemblages with highly significant correlations found for both seine and gill net species abundance data. A general decline in species diversity with distance from the mouth is probably a response to the greater osmoregulatory stress and diminishing food resources (see also Section 7) with increasing salinity, thus providing limited opportunities and for only the few highly salt-tolerant species. This is best exemplified by the dominance of *Atherinosoma microstoma* in the hypersaline North Lagoon and its occurrence as the only species that could tolerate the extremely hypersaline South Lagoon, where it was found in salinities up to 134 g/L. As a result, the structure of fish assemblages in the Murray Mouth and Coorong region (which can be considered typical of assemblages of the region during a drought) is primarily attributed to the distribution and abundance of this keystone species, with secondary influences of *Aldrichetta forsteri*, *Hyperlophus vittatus* and *Arripsis truttaceus* also important.

6.5. Understanding fish movement in the Coorong using otolith microchemistry

Fish have the ability to move within the Coorong, and between the Coorong, Lower Lakes (via fish ladders or locks on the barrages) and Southern Ocean. Their abundances within the Coorong are likely influenced by their ability to avoid high salinities and/or use different waterbodies over their lifetime. Conventional tagging techniques to track these movements are not possible since many of the fish are small. Gillanders and Munro (2009) explored the use of changes in otolith microchemistry with changes in salinity as a tool for tracking fish movements between waterbodies that differ in salinity using the Smallmouth Hardyhead *Atherinosoma microstoma*. This technique also provides the potential to determine longer historical perspectives on exposure to different salinities for longer-lived species.

Water samples and Hardyhead fish were collected from 10 sites along the Coorong, ranging in salinity from 6 to 123 g L\(^{-1}\), on six occasions over a 14-month period. Water (Ca, Ba, Mg, Mn and Sr) and otolith (Ba:Ca, Sr:Ca, Mg:Ca, Mn:Ca, Na:Ca, Li:Ca, \(\delta^{13}C\) and \(\delta^{18}O\)) elemental and isotopic concentrations were measured. Water strontium (Sr), magnesium (Mg) and calcium (Ca) exhibited conservative behavior (i.e. concentrations increased with salinity), whereas manganese (Mn) and barium (Ba) exhibited non-conservative behaviour along the salinity gradient. Water Ba showed a steep negative decrease from near freshwater to marine salinities followed by a gradual increase with increasing hypersalinity, a pattern not previously reported in the literature. Four of the six otolith element:Ca ratios and \(\delta^{18}O\) showed significant patterns with salinity, but the best fit model was often a segmented regression with one or two breakpoints. Positive linear relationships were also found between otolith Ba:Ca and water Ba:Ca, as well as otolith Mg:Ca and water Mg:Ca ratios. These results imply that it is possible to reconstruct the
past salinity environments experienced by individual fish but that several elemental and isotopic ratios and multivariate relationships will be required to determine if fish have been exposed to hypersaline conditions.

### 6.6. Current condition of the Coorong fish community

The continuation of the drought and an ongoing lack of freshwater inflows to the Murray Mouth and Coorong region are believed to have negative implications for Black Bream *Acanthopagrus butcheri*, Greenback Flounder *Rhombosolea tapirina*, Mulloway *Argyrosomus hololepidotus* and Congoli *Pseudaphrites urvillii*. It is unknown if or how the remaining three key fish species of the region are affected (*Yelloweye Mullet Aldrichetta forsteri*, Smallmouth Hardyhead *Atherinosoma microstoma* and Tamar River Goby *Afurcagobius tamarensis*).

It is highly likely that the extended drought conditions, lack of freshwater input and increases in salinity throughout the Murray Mouth and Coorong have influenced the composition of fish assemblages observed in this study. The current study provides a baseline against which future quantitative assessments can be compared. If a normal flow regime were to return to the region, this type of study should be repeated in order to understand whether and how the composition of fish assemblages in this region responds to a more regular inflow of freshwater.

### 6.7. Changes to the distribution and abundance of waterbirds

The Coorong has traditionally supported a wide range of waterbird species including endemic and migratory shorebirds (stilts, avocets, sandpipers and plovers), piscivorous species (terns, cormorants and pelican) and waterfowl (ducks and swan) (Rogers and Paton 2009b). An analysis of the spatial and temporal distribution of waterbirds along the Coorong revealed a progression of distinct waterbird communities that were geographically related to the wetland’s salinity gradient. Hypersaline ecosystems in the southern Coorong supported a distinct waterbird community that differed from those found in the marine and estuarine ecosystems in the northern Coorong. These results highlight the importance of maintaining a diversity of wetland systems within the Coorong.

While the spatial distribution of these communities along the Coorong was relatively stable in the short-term (~5 years), analyses of long-term datasets suggest that the nature of these communities had changed over the scale of decades, such that the waterbird community structure observed in the South Lagoon in 1985 no longer occurred in the Coorong (Table 6.1). While such changes in the waterbird communities may be a reflection of the spatiotemporal dynamics of the system, analyses of individual species showed that these long-term community changes were a result of significant declines in the abundance of most waterbird species, including those that dominated the South Lagoon waterbird community in 1985. Furthermore, declines in the abundance of key waterbird species between 1985 and 2000 have intensified in recent years, such that some species are rarely recorded in parts of the Coorong where they were once considered common.
Table 6.1. Common (maximum count of >100 individuals in any one year) waterbird species recorded in the South Lagoon of the Coorong in 1985 and between 2000 and 2007. The total abundance for each species is given for January 1985, along with the mean (± SEM) abundance for January, and abundance range, for the eight years between 2000 and 2007. The % change is the percentage increase (positive, in black) or decrease (negative, in red) in abundance relative to the species’ abundance in 1985 (calculated using the mean abundance for the period 2000–2007). The eight ‘key bird species’ studied in more detail during CLLAMMecology are shaded grey.

<table>
<thead>
<tr>
<th>Species</th>
<th>1985</th>
<th>2000-2007 (X±SE)</th>
<th>2000-2007 (Range)</th>
<th>% change</th>
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<tr>
<td>Australian Pelican Pelecanus conspicillatus</td>
<td>6045</td>
<td>1370.9 ± 320.4</td>
<td>394-2600</td>
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<tr>
<td>Little Black Cormorant Phalacrocorax sulcirostris</td>
<td>1190</td>
<td>72.3 ± 52.1</td>
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<tr>
<td>Great Crested Grebe Podiceps cristatus</td>
<td>263</td>
<td>19.4 ± 11.2</td>
<td>0-94</td>
<td>-92.6</td>
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<tr>
<td>Hoary-headed Grebe Poliocephalus poliocephalus</td>
<td>16766</td>
<td>2517.9 ± 954.7</td>
<td>50-8141</td>
<td>-85.0</td>
</tr>
<tr>
<td>Black Swan Cygnus atratus</td>
<td>676</td>
<td>275.1 ± 58.3</td>
<td>68-526</td>
<td>-59.3</td>
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<tr>
<td>Australian Shelduck Tadorna tadornoides</td>
<td>6059</td>
<td>3290.4 ± 625.3</td>
<td>1339-6242</td>
<td>-45.7</td>
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<td>Grey Teal Anas gracilis</td>
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<td>8727.1 ± 2692.8</td>
<td>2446-24460</td>
<td>-85.2</td>
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<tr>
<td>Chestnut Teal Anas castanea</td>
<td>660</td>
<td>4110.8 ± 989.1</td>
<td>430-10147</td>
<td>+522.8</td>
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<td>White-faced Heron Ardea novaehollandiae</td>
<td>128</td>
<td>39.1 ± 8.4</td>
<td>15-75</td>
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<tr>
<td>Common Greenshank Tringa nebularia</td>
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<td>59.6 ± 10.6</td>
<td>16-103</td>
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<td>Sharp-tailed Sandpiper Calidris acuminata</td>
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<td>2218.4 ± 515.7</td>
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<td>Red-necked Stint Calidris ruficollis</td>
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<td>15-113</td>
<td>-58.0</td>
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<td>Masked Lapwing Vanellus miles</td>
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<td>2830.4 ± 895.0</td>
<td>1077-8445</td>
<td>-30.8</td>
</tr>
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<tr>
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<td>877-8186</td>
<td>-50.7</td>
</tr>
</tbody>
</table>

The abundance of key waterbird species was related to the abundance of key food resources in an attempt to understand the recent changes in bird abundance in the South Lagoon. Observed declines in abundance of Black Swan Cygnus atratus in the South Lagoon were significantly correlated with observed declines in the cover of Ruppia tuberosa, the only aquatic macrophyte found in the South Lagoon in recent years. Similar correlations were detected in the South Lagoon between the Smallmouth Hardyhead Atherinosoma microstoma and two piscivorous bird species, Fairy Tern Sterna nereis and Australian Pelican Pelecanus conspicillatus. No relationships were detected between the abundance of Ruppia propagules (seeds and turions) and Tanytarsus barbitarsus (Chironomidae) larvae, and the abundance of any of the three Calidris shorebird species that typically feed on these resources in the South Lagoon. This result was surprising, given the fundamental role of the Coorong in the ecology of these species is providing non-breeding foraging habitat. However, other food sources, such as the Australian...
Brine Shrimps (*Parartemia zietziana*) may have partly compensated for reductions in typical food resources for these species.

Analyses of the foraging behaviour of these shorebird species indicated that foraging performance declined with increasing water depth. This response was observed over very small differences (i.e. 20–30 mm) in water depth, implying that the foraging performance of these species is very sensitive to changes in water depth. Furthermore, the foraging performance of all three species also declined with distance from the shoreline in cases where individuals were foraging on exposed mudflats. This relationship was most likely related to higher elevations further from the shoreline, which in turn, were related to the lower inundation frequency at these higher elevations. As with water depth, shorebird foraging performance was very sensitive to distance above the waterline, with reductions in the rate of foraging attempts occurring over distances of 5–10m from the waterline, or less.

The management implications of these results focus on the direct and indirect responses of birds to hydrological regimes in the Coorong. Responses are likely to be indirect for most bird species, through the responses of their preferred food sources. As such, management for the maintenance of these bird species requires an understanding of the requirements of prey species, and management strategies that provide these requirements in the Coorong. In addition, some species such as the calidrine waders also show strong responses to the physical environment. The responses of these species will be linked to interactions between water level regime and mudflat topography. Those responsible for managing the Coorong ecosystems need to account for the hydrological implications of physical habitat availability, as well as the requirements of prey species, when managing for the wetland’s waterbird species.

6.8. Prognosis

The on-going absence of environmental flows will continue to threaten the distribution and abundance of the Coorong’s biota. The increasing salinity along the length of the Coorong appears to be the critical factor. Although the northern reaches near the Murray Mouth may not exceed marine salinities, this region no longer experiences the lower estuarine salinities that were more typical prior to the cessation of environmental flows. Essentially there is no longer an estuary. Salinity is a major determinant of distribution and abundance of the majority of aquatic biota within the Coorong. It directly influences fish, and benthic invertebrates and indirectly influences bird species. Further contractions in distribution and abundance should be expected if salinities continue to rise. Elevated salinities have been particularly significant in the southern Coorong where the salinities are now consistently four to six times those of seawater and well above the upper thresholds of key biota that formerly dominated this lagoon, including the highly saline tolerant fish, the Smallmouth Hardyhead *Atherinosoma microstoma* and the larvae of the chironomid *Tanytarsus barbitarsus*.

*Ruppia tuberosa* has all but disappeared from the South Lagoon but its disappearance may not be due or solely due to rising salinity. Its contraction has led to significant reductions in the abundances of most waterbird species in the South Lagoon. Those high salinities have also allowed one species the Australian Brine Shrimp *Parartemia zietziana* to flourish, and one bird species the Banded Stilt (*Cladorhynchus leucocephalus*) has prospered. Despite the significant changes in recent years; and significant contractions in distribution and reductions in abundance of the aquatic biota of the Coorong, the region still maintains a diversity of ecological communities and remains one of the best habitats for waterbirds in the Murray-Darling Basin.
7. Coorong Food Webs

Food webs attempt to describe how energy is transferred across an ecosystem, in other words, ‘who eats what’. It is important to understand what food webs are present in the Coorong and how they could change following management intervention given the region’s significance as a feeding ground for fish and waterbirds. As a component of the Sustaining Food Webs theme, food webs leading to predatory fish (Yelloweye Mullet *Aldrichetta forsteri*, Black Bream *Acanthopagrus butcheri*, Greenback Flounder *Rhombosolea tapirina* and Mulloway *Argyrosomus hololepidotus*) were evaluated along the Coorong salinity gradient using a combination of gut content and stable isotope analysis (SIA) for carbon ($\delta^{13}$C), nitrogen ($\delta^{15}$N) and sulfur ($\delta^{34}$S). In SIA analysis, predators acquire their isotopic signature from the prey they eat. As prey have different isotopic signatures, it is possible to infer what predators have been eating. In addition, the nitrogen stable isotope signature in predators is slightly enriched relative to the prey they eat. This property can be used to measure how many ‘steps’ (the food chain) are present in a food web and to provide a quantitative measurement of the trophic level of a given organism in the food chain (their position, on average, in the food chain). SIA analysis also integrates the average diet over longer periods of time (usually months) than gut content analyses (hours to days).

Three investigations were undertaken to examine the trophic interactions within the Coorong (Deegan *et al.*, 2009). The first examined the influence of the Coorong salinity gradient on the baseline isotopic signatures of its food webs, a necessary step before undertaking SIA analysis. The second investigation examined how the food web structure varied along the Coorong salinity gradient. As SIA analysis integrates the diet of fish over time, this property was used in the third study, to infer the preferred feeding areas for predatory fish in the Coorong.

7.1. Baseline isotopic signatures

Primary consumers (herbivores) did not have a constant stable isotope signature for C, N and S along the Coorong salinity gradient. The $\delta^{15}$N and $\delta^{34}$S values of first order consumers increased significantly with increasing salinity, whereas the $\delta^{13}$C values decreased slightly although this decline was not statistically significant. Water depth did not appear to influence the baseline isotopic signatures of first order consumers at one intensively studied site (Pelican Point). How the salinity gradient influences the baseline signatures remains unclear. The implications of this study are that prey stable isotope signatures must be measured across the Coorong salinity gradient before undertaking SIA.

7.2. Food web structure along the Coorong salinity gradient

Changes in the food web structure along the Coorong salinity gradient were extensive. There was a loss of trophic guilds (groups of organisms performing a similar ecological function) over a relatively short distance (Murray Mouth to Pelican Point) as salinity increased. The food web became shorter as species and guild diversity decreased along the salinity gradient. This was particularly apparent from the decrease in $\delta^{15}$N in the larger bodied fish species with increased salinity (Figure 7.1). Black Bream *Acanthopagrus butcheri*, Mulloway *Argyrosomus hololepidotus* and Greenback Flounder *Rhombosolea tapirina* decreased in trophic position with increased salinity. This suggests that predatory fish had to feed on less preferred food sources (probably smaller prey) as they foraged in higher salinity habitats. Mulloway and Black Bream are the top fish predators in the Coorong. However, smaller Mulloway were at a higher trophic level than larger ones in the Murray Mouth, possibly because larger mulloway have a high proportion of crab in their diet (which are at a lower trophic level than prey fish).

7.3. Stable isotopes identify both dietary sources and source location

In a preliminary study, Lamontagne *et al.* (2007) found that fish caught at Pelican Point had limited overlap in isotopic signature with prey at this site, suggesting they mostly foraged
elsewhere before being caught. SIA and a mixing model were used to infer where predatory fish fed in the Coorong. The mixing model suggested that Smallmouth Hardyhead *Atherinosoma microstoma* sampled at both Goolwa and Long Point, together with juvenile Mullet sampled at Goolwa, foraged at alternate but nearby locations to where they were caught. Likewise, Black Bream sampled at Mundoo appeared to be utilising food resources from Goolwa Channel. The isotopic signatures of large Greenback Flounder sampled at Goolwa reflected prey source signatures from Pelican Point. Mulloway sampled at Mundoo, Goolwa and Pelican Point appeared to be using food resources from both Goolwa and Pelican Point. No fish sampled appeared to be using resources from Mundoo, even though Mulloway were sampled there. The results indicate that Mulloway found within the Coorong were feeding throughout the region between Goolwa Channel and Pelican Point, but not significantly at Mundoo Channel in the months preceding the study (November 2007).

The key implication of this research is that habitat quality for predatory fish decreases with increasing salinity in the Coorong because a smaller diversity of prey is available.

*Figure 7.1.* Food chain length leading to predatory fish along a salinity gradient in the Coorong (from Deegan *et al.* 2009). The trophic position of predatory organisms was estimated based on their increase in $\delta^{15}$N relative to known primary consumers (trophic level 2), which included filter-feeders, algal grazers, etc. Mulloway *Argyrosomus hololepidotus*; Black Bream *Acanthopagrus butcheri*; Greenback Flounder *Rhombosolea tapirina*; Yelloweye Mullet *Aldrichetta forsteri*; Smallmouth Hardyhead *Atherinosoma microstoma*; Congolli *Pseudaphritis urvillii*. 
8. Ecosystem State Models of the Coorong

One of the objectives of CLLAMMecology was to develop an ecosystem response model to enable the prediction of changes in ecological condition under a range of possible future scenarios. An ecosystem response model translates information about the physical and chemical characteristics of a region into predictions regarding how the various biota will respond to changed conditions. The model reflects the collective nature of both the living and non-living parts of the environment.

For the Coorong, the model used information regarding weather, hydrology (e.g. water levels and tidal influence), salinity, and other water quality variables as the environmental (physico-chemical) variables possibly driving the ecological responses in the system. These were used to predict the mixture of aquatic vegetation (including *Ruppia tuberosa*), fish, birds and macroinvertebrates that would be found at each focal site in each year. Given the patchiness of the available data, this was done using statistical techniques rather than attempting to model all relationships mathematically (Lester and Fairweather 2008). Not all data were available for all sites at all times, which was one of the major challenges of the research, but the most complete data set available was used.

The model was built as a state-and-transition (S&T) model (Lester and Fairweather 2009; Lester and Fairweather *in press* a,b). A S&T model assumes there are a limited number of distinct ecosystem states that can occur in a region, and that these are separated by discrete thresholds of one or more environmental variables. An ecosystem state is a combination of the biota that occur together (for example, a mixture of birds, fish and vegetation species), along with a set of environmental characteristics that govern where that state is found both in space and time. A particular site will exist in one state until a threshold value is crossed, then it will change into another state (depending on which threshold is crossed), and remain until another threshold value is crossed.

The ecosystem state model developed for the Coorong identified eight distinct ecosystem states (Figures 8.1 and 8.2; Lester and Fairweather 2009). These were divided into two sets; with one set being tidally influenced (Figure 8.3), and the other with very little or no tidal influence (Figure 8.4). The environmental variables driving the transitions between states were tidal influence (as mentioned), the number of days with no flow over the barrages, water levels, water depths from the previous year and salinity (Figure 8.1). Within each set, there appeared to be a continuum of states, ranging from healthy to degraded. This is because the threshold for the number of days without flow was 339 days (or about 11 months) – a situation that occurs in the Coorong less than 1% of the time, on average. The eight states were named Estuarine/Marine, Marine, Unhealthy Marine, Degraded Marine, Healthy Hypersaline, Average Hypersaline, Unhealthy Hypersaline and Degraded Hypersaline (Figures 8.3 and 8.4).

Each of the states supported a distinct set of biota (Figures 8.1 and 8.2) and was associated with a distinct set of environmental conditions (Lester and Fairweather 2009). For example, the Average Hypersaline state had frequent freshwater flows over the barrages and quite high nutrient concentrations in the water column. Salinity was higher than for seawater due to natural evaporation along the length of the Coorong. *Ruppia tuberosa* was commonly found, with a variety of waterbird species and wading birds in high abundances. Insect larvae and amphipods were characteristic of the macroinvertebrates associated with this state. The Degraded Hypersaline state, however, had the highest salinity of all states along with the lowest water levels. The length of time with no flows over the barrages was the second highest of all states. Only one fish species, the Smallmouth Hardyhead *Atherinosoma microstoma*, was characteristic of the state. Banded stilt *Cladorhyncus leucocephalus* was the most common bird species found, suggesting that Australian brine shrimp *Parartemia zietziana* (their main food) numbers were also high. Very few other invertebrate species would have been able to tolerate the high salinity. It is likely that *Ruppia tuberosa* would also be absent from this state.

There are a number of uncertainties associated with the current ecosystem state model, particularly surrounding any potential for recovery within the system. This is because of the
degraded state of the Coorong during the nine years that supplied much of the data used to build the model. Further monitoring work, focused on the biological and environmental parameters used by the model is recommended to confirm (or otherwise) the modelling predictions.

Despite these limitations, this model has the potential to assist managers in the development of more rigorous management targets and monitoring programs (Lester and Fairweather in press a,b). The ecosystem state model simplifies the task of defining ecosystem condition because managers can use a mixture of ecosystem states as a target. It also helps define the limits of acceptable change within the system, by providing a range of values for each variable driving the ecosystems within which, the ecosystem state will remain stable. This is a significant improvement over the current system, where indicator species and targets for environmental variables might be chosen by expert opinion alone, rather than using the available data for the region. The ecosystem state model is a data-driven, multivariate representation of a complex system that can be used in simple assessments of ecological condition, or in detailed scenario analyses.

Figure 8.1. Ecosystem state model for the Coorong. This figure presents a logic tree that can be followed to identify the ecosystem state for a given location and time in the Coorong. Each white box with a light blue shadow contains a splitting parameter and a threshold value. Where the value for the parameter is less than or equal to the threshold value, then the tree should be followed to the left. Where it is higher, the tree should be followed to the right. When a coloured terminal node box is reached, the state has been identified.
Figure 8.2. Distribution of ecosystem states along the Coorong. a) In 1999 to 2001, b) In 2002, c) In 2003, d) In 2004 to 2005, e) In 2006, f) In 2007. Note: Dotted lines indicate boundaries between the three regions. Dots indicate the locations of the focal sites (see Figure 1.1 for names). Names of regions are only listed on panel a, but apply to all other panels as well.
Figure 8.3. Conceptual diagrams illustrating the characteristic taxa for each ecosystem state in the marine basin. a) Estuarine/Marine, b) Marine, c) Unhealthy Marine, d) Degraded Marine. Note: This diagram is a conceptual characterisation designed to illustrate the suite of species characterising each state. It does not illustrate all species present, nor the most abundant species necessarily. Instead, it shows those species that distinguish this state from the others. The number of organisms depicted and their relative size is not to scale, and the geomorphic setting is not realistic. Differences in average water level are shown as a retreat from the shoreline and average salinity is indicated by a colour-coded bar in the water column, using a continuum from low to high. Red crosses indicate the loss of taxa compared to the Estuarine/Marine state. Species lists can be found in Lester and Fairweather (2009).
Figure 8.4. Conceptual diagrams illustrating the characteristic taxa for each ecosystem state in the hypersaline basin. a) Healthy Hypersaline, b) Average Hypersaline, c) Unhealthy Hypersaline, d) Degraded Hypersaline. Note: This diagram is a conceptual characterisation designed to illustrate the suite of species characterising each state. It does not illustrate all species present, nor the most abundant species necessarily. Instead, it shows those species that distinguish this state from the others. The number of organisms depicted and their relative size is not to scale, and the geomorphic setting is not realistic. Differences in average water level are shown as a retreat from the shoreline and average salinity is indicated by a colour-coded bar in the water column, using a continuum from low to high. No data were available regarding macrophyte distribution for the Healthy Hypersaline and Degraded Hypersaline states, nor for water quality, commercial fish catch or macroinvertebrate distributions for the Degraded Hypersaline state, so these are not depicted. Species lists can be found in Lester and Fairweather (2009).
9. Future Scenario Analyses

Decision-makers need to understand the future ecological consequences of their decisions to effectively manage the Coorong. The hydrodynamic (Section 2) and the ecosystem state (Section 8) models were used to predict the likely consequences of 20 possible future climate and management scenarios for the Coorong and Murray Mouth region (Lester et al. 2009). These scenarios were defined following consultations with a range of experts and stakeholders and represent plausible conditions for the region in the middle of the century. While comprehensive, these scenario analyses are not exhaustive. The aim was to demonstrate how the framework can be used and to have a first look at the potential effectiveness of management levers under different possible future climates.

Future climate is an important consideration for the design of scenario analyses for the region because it will determine runoff from the Murray-Darling Basin and evaporation rates in the Coorong and Murray Mouth region. The climate component for the scenario analyses was defined using a subset of the scenarios from the Murray-Darling Basin Sustainable Yields Project (CSIRO 2008), which estimated the water regime of the River Murray under different ~2030 climates. This provided synthetic 114-years time series of River Murray flows and evaporation rates in the Coorong under ‘historical’, ‘natural’, slightly warmer (‘Median Future’) and much warmer (‘Dry Future’) climates. Another climate change consideration was the potential for sea level rise, which has been forecast to be between –10 to +40 cm in Encounter Bay by mid-century.

In addition to different future climates, the scenarios also included different combinations of the use of three potential management levers – environmental flows, dredging at the Murray Mouth and releases from the Upper South East Drainage scheme (USED). The modelled flow scenarios from the Murray-Darling Basin Sustainable Yields Project do not include future provisions for environmental flows. The potential effects of environmental flows were assessed by using one possible flow recovery scenario within the range proposed by The Living Murray initiative (Murray-Darling Basin Commission 2006). The 20 scenarios investigated by CLLAMMecology are summarised in Table 9.1 and presented in more detail in Lester et al. (2009), Langley et al. (2009) and Lester and Fairweather (in press b).

From investigation of a Baseline scenario (using an historic climate and current water extraction levels in the Basin), it was clear that the current condition in the Coorong is exceptional, even compared with 114 years of meteorological variation. No other drought in the sequence produced conditions as poor as are currently observed in the Coorong.

Water extraction levels had a significant impact on both the hydrology and the ecosystem states of the Coorong. Under natural flows (i.e. no water storages or extractions in the Murray-Darling Basin), ecosystems were predicted to be in a much healthier mix of states than is currently the case (Figures 9.1 and 9.2).

Under current extraction levels, future climate change has the potential to be devastating for the ecology of the Coorong. Salinities are predicted to rise dramatically under a dry future climate projection and the lagoons could experience up to eight years without any flow over the barrages. The effect of this on the ecosystem states of the Coorong was dramatic, with sites predicted to be in a degraded state for almost half of all years. On the other hand, the effect of climate change was much smaller under natural flow conditions, indicating it was the combination of climate change and current extraction levels driving the dire predicted mix of ecosystem states, rather than climate change alone.

Changes in sea level had a mixed impact on the hydrodynamics and ecosystem states of the Coorong. Sea level rise, both at a moderate or high level (i.e. 20 or 40 cm rise), increased the hydrodynamic connectivity in the Coorong, and thus alleviated some of the more severe effects of climate change at current extraction levels. However, these effects were not fully reversed, and the ecosystem states of the Coorong were a more degraded mix than observed for the Baseline scenario.
Relatively small amounts of additional environmental water delivered to the Coorong, via The Living Murray (TLM) initiative could have a large impact on the ecosystem states in the Coorong. By providing additional flows at times of drought, TLM had the capacity to alleviate many of the effects of prolonged drought. There was, however, a note of caution with this scenario. The inclusion of TLM infrastructure without the delivery of environmental water actually caused a slight deterioration in the condition of the Coorong. This emphasises the need to actually deliver the environmental water as planned once the necessary infrastructure is in place.

Under the scenarios investigated, increased Murray Mouth dredging had quite a limited effect on the connectivity and ecosystem states of the Coorong but the proposed augmentation of the USED scheme had a greater impact. This does not mean that dredging is not environmentally beneficial but that the benefits were mostly apparent in the North Lagoon and did not compare with the benefits derived from barrage flows. The effect of additional water through the USED scheme influenced the ecosystem states in the South Lagoon regularly, and sites as far north as the Murray Mouth occasionally. This option had the potential to buffer the Coorong in times of drought, if the water was available.

![Figure 9.1](image-url)

**Figure 9.1.** Frequency of occurrence of ecosystem states (as a percentage of site-years) at the 12 focus sites over simulated 114-year periods for different climate and management scenarios for the Coorong and Murray Mouth. Note the 12 focus sites are not evenly distributed across the region (with more sites in the Murray Mouth and fewer in the South Lagoon relative to their surface area; refer to Figure 1.1). EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DM = Degraded Hypersaline.
Figure 9.2. Comparing hydrodynamic drivers of ecosystem states for climate and management scenarios for the Coorong: (left) marine sites; (right) hypersaline sites. These analyses indicate that potential future reductions in River Murray inflows forecast under ‘drier’ future climates would have a strong impact on the ecological character of the Coorong and Murray Mouth region. Note: Refer to Table 9.1 for explanation of which scenarios are represented by each symbol. The baseline scenario is not represented independently, as all other scenarios are shown relative to it (i.e., at the origin). The Murray Mouth Dredging and Max USED Flows scenarios used an alternative ecosystem state model with different hydrodynamic drivers so they are not shown either. This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to the hydrodynamic variables driving ecosystem states. The length of each vector is proportional to the strength of the deviation from the Baseline condition (as shown by the 0,0 origin). Vectors in the quadrant shaded blue for each panel indicate an improvement for both driving variables.

9.1. Summary of scenario analyses

Climate and extraction from the River Murray will be the two strongest determinants of the ecological condition of the Coorong in the future. At current extraction levels across the Murray-Darling Basin, the forecast reductions in River Murray inflows to the region under a ‘dry’ future climate scenario would lead to significant further ecological degradation of the Coorong. However, sea level rise may partially ameliorate the condition of the Coorong under this ‘dry’ scenario. While increased Upper South East Drainage scheme releases and Murray Mouth dredging may bring some environmental benefits, the most effective management lever in the scenario analyses was clearly increased environmental flows from the barrages.
Table 9.1. Summary of scenarios investigated. Note: ‘+’ denotes current levels or observed present in the scenario and ‘-’ indicates none or not present in the scenario. The last two columns refer to the vectors representing scenarios in Figure 9.2.

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<th>Mouth dredging</th>
<th>Sea level rise</th>
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10. Conclusion and Recommendations

The first contribution of this project was to have significantly advanced the ecological knowledge of the Coorong. While not as comprehensive as the work in the Coorong, the limnological surveys of the Lower Lakes undertaken during CLLAMMecology are also the most detailed to date for this system, in particular with regards to offshore water quality. The coordinated research effort allowed the study of multiple aspects of the ecology of the Coorong, including some topics, such as nutrient cycling, which had received limited attention before. Because this study occurred during a period when there was no flow over the barrages, it provides an ecological ‘baseline’ to compare with future environmental flow experiments for the region.

The basic ecological information collected during this study can be found in a series of reports available at the web site:


In addition, a metadatabase of the information collected during the study has been compiled by SARDI Aquatic Sciences and can also be accessed through the project web site.

The second contribution of CLLAMMecology is to have produced an ecological framework to help plan the management of the Coorong. The framework has two basic components:

- A hydrodynamic model to forecast changes in water level and salinity in the Coorong and Murray Mouth at decadal scales and longer, and
- Ecological information and models to predict changes in the distribution of key species, habitats, and ecosystem states following changes in water level, salinity and other factors.

Some of the new information and ecological models developed during CLLAMMecology include:

- A GIS model to predict the distribution of potential habitats in the Coorong, such as mudflats with a particular inundation regime (Sharma et al. 2009);
- Models of fish distribution based on their salinity tolerance (Noell et al. 2009; Sharma et al. 2009);
- The determination of the suitable salinity and water level regime for key macroinvertebrate species (Rolston and Dittmann 2009);
- A preliminary model to predict the distribution of *Ruppia tuberosa* in the Coorong (Rogers and Paton 2009a);
- Empirical relationships to predict the abundance of Black Swan, Fairy Tern and Australian Pelican in the South Lagoon based on the abundance of their favourite food source (Rogers and Paton 2009b);
- The determination of the water depth on mudflats suitable for effective foraging by three *Calidris* shorebird species (Rogers and Paton 2009b);
- An ecosystem state-and-transition model for the Coorong (Lester and Fairweather 2008; Lester and Fairweather in press a,b).

While it was outside the scope of CLLAMMecology to produce a ‘hands-on’ version of the whole ecological framework, it would be possible to do so with further work. At present, the framework can be used in consultation with the agencies responsible for developing its different components. This is not necessarily a drawback because experience has shown that designing plausible future climate and management scenarios is in itself a complicated task because of the complexity and inherent constraints in the use of the potential management levers. Thus, an important legacy of this project is to have provided a platform to help scientists and managers interact and design better management strategies for the region.

In addition to the scientific knowledge and management tools produced, an ongoing legacy of the project is the new links that have been generated between the different participating
research institutions. The project has also substantially contributed to the training of the next generation of environmental scientists for the region, in particular through the training of eight postdoctoral research fellows.

10.1. Limitations of the framework

There are limitations to what can be achieved through the use of the proposed framework and its individual models. While it is clear that the water level and salinity regimes are strong environmental drivers in this system, the mechanisms by which they impact on particular species are not always known. As a result, many of the models developed during this project are empirical in nature. Secondly, most of the detailed ecological information about the region is relatively recent and was collected during a period when the environment was degrading. However, ecosystem ‘recovery’ following improvements in environmental conditions may not necessarily follow the same path taken during ‘degradation’. For example, the return of *Ruppia tuberosa* to the South Lagoon may take longer than anticipated if its propagule bank becomes depleted before suitable environmental conditions return. While significant progress has been made in recent years, there remain many scientific uncertainties about how key species respond to changes in environmental conditions in the region. Future management interventions in the region should be considered as opportunities to study some of these knowledge gaps. Ecological models of the region could also be improved by attempting to reconstruct pre-1985 environments through the combination of paleoecological records, historical information and knowledge of Indigenous people.

The framework does not currently include a geomorphic component, a limitation to assess the potential impacts of sea level rise on the very longer-term (end of the century and beyond). However, the current framework should be sufficient to assess the impact of sea level rise over the next fifty years or so, which is forecast to be somewhere between –10 cm to +40 cm in Encounter Bay. Further investigations will be required to assess how additional increases in sea level will impact on the behaviour of the Murray Mouth channel and on some of the lower-lying barrier sand dunes between Encounter Bay and the Goolwa Channel (Mathews 2005).

The framework does not evaluate the social, cultural and economic costs and benefits associated with management intervention in the region. However, one preliminary study on the non-market values of the Coorong was made (Dyack *et al.* 2007) and the output from the framework can be used as input for socio-economic analysis. Preliminary engagements to include members of Indigenous communities as research partners have been made, as requested in the Ngarrindjeri Sea Country Plan (Ngarrindjeri Nation 2007), and should be pursued in future research programs for the region.

10.2. Key recommendations

Through CLLAMMecology, a scientifically verified understanding of the linkages between physical interventions and ecological impacts has been developed which is encapsulated in a modelling framework. As this understanding and framework are sufficiently robust, it is recommended that the framework be used to guide management of the Coorong for achieving ecological objectives.

The principal focus of CLLAMMecology was on the Coorong because this was the region of concern for management at the time the study was designed. Since then, the ecological status of the Lower Lakes has also degraded following a period with very low River Murray inflows. The approach undertaken during CLLAMMecology to understand the relationships between management levers, key environmental drivers and their impact on ecological processes is also applicable to the Lower Lakes. CLLAMMecology therefore recommends a similar framework for management of the Lower Lakes.

While progress was made, there remain a number of knowledge gaps in the ecology of the Coorong. This is due, in part, to the most detailed studies of the region having been made during a period when it was gradually degrading (especially from the late 1990s onward). Many knowledge gaps could be addressed by studying the ecology of the Coorong during periods
when significant freshwater flows occur through the barrages. CLLAMMecology recommends using future environmental flows from the barrages as opportunities to improve the understanding of the ecology of the Coorong. As significant flows through the barrages are unlikely to occur in the next few years, there is an opportunity to design and plan a follow-up study to CLLAMMecology targeting a period with significant environmental flows to the Coorong.
11. References

11.1. CLLAMMecology publications


### 11.2. Other publications


